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Original Article

The Global Atmospheric Pollution Forum (GAPF) emission inventory preparation tool and its application to Côte d'Ivoire

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ABSTRACT

Low- and middle-income countries (LMICs) often lack the necessary tools, guidance, and capacity for compiling an emission inventory (EI) for air pollutants. A reliable EI is an important prerequisite for the identification of key emissions sources, as an input to modelling atmospheric transport and impacts of air pollutants, and the identification of appropriate mitigation policies. The publicly-available Global Atmospheric Pollution Forum Emission Inventory (GAPF-EI) tool meets the need of LMICs for a user-friendly tool allowing in-country practitioners to compile their own EIs. The species covered are SO_2, NO_X, CO, NMVOC, CH_4, NH_3, PM_{10}, $PM_{2.5}$, black carbon, organic carbon and CO_2. Output from the tool can therefore support the development of integrated air quality and climate change mitigation strategies. This tool incorporates default emission factors and inventory methods conforming with internationally recognised approaches. The GAPF-EI tool enables emissions to be estimated for technologies or practices that are often of little or no relevance to developed countries, but may represent key sources in LMICs. This paper describes the GAPF-EI tool and its application to Côte d'Ivoire where emissions from traditional biomass cookstoves, vegetation fires, traditional charcoal manufacture, road transport (including dust from unpaved roads) and open burning of municipal solid waste were found to be particularly important components of the inventory. The application of the GAPF-EI approach to Côte d'Ivoire has demonstrated its utility in addressing sources of particular relevance to LMICs in addition to providing a user-friendly, transparent and flexible EI preparation tool.

1. Introduction

Elevated atmospheric concentrations of air pollutants can have adverse impacts on human health including increased morbidity and mortality. Low- and middle-income countries (LMICs), i.e. those countries not defined as high-income economies by the World Bank (World Bank, 2020), are disproportionately affected, with over half of the mortality burden attributable to fine particulate matter ($PM_{2.5}$) occurring in China and India (Health Effect Institute, 2019). Atmospheric emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_X), and ammonia (NH_3), in addition to being precursors of secondary PM, are associated with ecosystem damage such as eutrophication and acidification (Fowler et al., 2009; Bobbink et al., 2010). Also, the phytotoxic effects of tropospheric O_3, formed in the atmosphere from NO_X, NMVOC, CH_4 and CO emissions under the action of sunlight, can lead to decreases in agricultural crop yields (Fuhrer, 2003; Fuhrer and Booker, 2003; van Dingenen et al., 2009; Avnery et al., 2011; Mills et al., 2018) reductions in forest biomass (Matyssek and Sandermann, 2003), and changes in species composition of semi-natural vegetation communities (Davison and Barnes, 1998; Ashmore, 2005). During the past few decades, emissions of most air pollutants have decreased in North America and Europe due to improved energy efficiency, fuel switching and emission controls whilst emissions continued to rise in many developing countries (Amann et al., 2013). More recently, progress has also been made on reductions of SO_2, NO_X and $PM_{2.5}$ in some developing countries, especially in Asia (IEA, 2016; UNEP, 2019). However, there are increasing concerns about the deteriorating state of the atmospheric environment over the African continent (UNEP, 2014; USEPA, 2016; Schwela, 2012; Assamoi and Liousse, 2010) due to rapid growth in population, GDP and rates of urbanisation (Olawoyin, 2019), with West Africa identified as one of the more polluted regions in Africa (Knippertz et al., 2015).

In addition to air pollution, human-induced climate change is also resulting in adverse impacts such as increased frequency of extreme

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weather events (including droughts, floods, and heat waves); sea level rise; and biodiversity loss – with most of the affected people living in LMICs (Allen et al., 2018). These countries are least able to cope with the impacts of climate change, and this is compounded by the additional and growing impacts of air pollution they are experiencing. In many highly industrialised countries, climate policies are often considered to be more important than air pollution policies whereas, in many LMICs, especially in their megacities, air pollution and the protection of human health is seen as a much more urgent issue (Grennfelt, 2009; UNEP, 2019). However, as emissions leading to air pollution impacts and climate change often have the same sources, there is a growing recognition of the benefits and synergies that can result from integrated strategies to reduce both air pollutant and greenhouse gas emissions (Adams et al., 2009; Shindell et al., 2012). There is also growing interest in addressing the short-lived warming substances, especially methane (CH_4), tropospheric ozone and black carbon (BC), sometimes jointly referred to as 'short-lived climate pollutants' (SLCPs) which have short atmospheric lifetimes, relative to CO_2. Ozone and BC both have adverse impacts on human health, and ozone reduces crop yields; strategies focussing on their reduction would slow the increase in global temperature over the next 20–40 years (UNEP/WMO, 2011; Shindell et al., 2012).

Quantifying the levels of air pollutants and GHGs emitted by different sources and activities is crucial to understanding and limiting the harm such emissions cause to human health, agricultural yields, natural ecosystems and the climate (Adams et al., 2009). Whilst parties to the UN Framework Convention on Climate Change (UNFCCC) are required to compile and report their GHG emissions, there are no institutionalized processes with a focus on establishing national inventories for air pollutants at the global level (Amann et al., 2013). Most air pollutant emission inventory activities have been conducted in developed countries, with reliable information lacking for the developing world (Monks et al., 2009). In Europe, North America and some Asian countries (including China, Japan and South Korea), there is official national reporting of emission inventories for a number of air pollutants. However, although air pollutant emission inventories are the basic building blocks of air quality (AQ) modelling and management, routine calculation of emission estimates of high quality are often absent in many LMICs with the capacity to undertake the necessary calculations also generally lacking. Without detailed and reliable emission inventories, there is little opportunity for countries to develop strategic plans for dealing nationally with their air pollution problems and to monitor the effect of such plans. Regional issues such as acidic deposition, eutrophication of sensitive ecosystems, tropospheric ozone formation and increasing atmospheric loads of fine PM also require harmonised, national emission inventories in order to develop regionally coordinated abatement strategies.

Global inventories of the main regional air pollutants include the Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2018) and the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2011). Regional emission inventories for Asia include the MIX inventory developed for the years 2008 and 2010 (Li et al., 2017), the Regional Emission Inventory in Asia (REAS) (Kurokawa et al., 2013), an inventory for the year 2000 to support the TRACE-P project (Streets et al., 2003) and an inventory for 2006 produced for the INTEX-B mission (Zhang et al., 2009). However, for Africa there is a general lack of detailed anthropogenic emission inventories at both continental and regional scales (Liousse et al., 2014). Also, in Latin America, there is often no national coverage for emissions of air pollutants at the level of detail needed for AQ policy support; most emission inventories currently used for AQ assessments in Latin America being derived from the global data sets (IGAC, 2018). Global and regional emission estimates compiled by different research groups are not always similar and differences can be especially large for developing world regions (Dentener et al., 2010). This emphasises the need for a tool that enables in-country practitioners within LMICs to compile detailed, national-scale inventories themselves.

This paper describes a novel methodological approach detailed in the Global Atmospheric Pollution Forum Emission Inventory (GAPF-EI) manual (Vallack and Rypdal, 2019) and its associated Excel workbook (Vallack, 2019), jointly referred to as the GAPF-EI tool. This tool was developed in order to provide a simplified, user-friendly framework for emissions inventory preparation suitable for use in LMICs that can estimate emissions of both air pollutants and the major GHGs. The GAPF-EI approach is also compatible with other major international emission inventory preparation approaches such as those described in the EMEP/EEA Guidebook (EMEP/EEA, 2016) and the IPCC Guidelines (IPCC, 2006). The GAPF-EI tool has recently been made publicly available, and further details about its development are given in the manual (Vallack and Rypdal, 2019).

The GAPF-EI is applied to Côte d'Ivoire to demonstrate the ability of the tool to quantify emissions that are likely to be rather specific to LMICs. We chose an LMIC in West Africa as this is a region where there are increasing concerns about the declining air quality but where robust national air pollutant emission inventories are generally lacking. This paper therefore reports on the results of a national emissions inventory compiled for Côte d'Ivoire (for the year 2010) using this tool, together with an uncertainty analysis of the estimated emissions. These results are compared with other regional and global initiatives that report emission estimates for Côte d'Ivoire. The relevance of building national-level EI capacity, especially given the recently identified urgent need to address SLCPs in addition to traditional air pollutants, is also emphasised.

2. Methodology

The GAPF-EI tool has been designed as a guide to in-country practitioners in LMICs to help them compile a national emission inventory of the major air pollutants and GHGs covering most sectors and technologies of relevance to such countries. The tool includes a user-friendly workbook where users can either input their own country-specific activity data if available, or use the suggested default international database sources. Similarly, users can either enter locally- or regionally-derived emission factors (EFs), where available, or the suggested defaults. In particular, the GAPF-EI tool allows emissions to be estimated for technologies or practices that are often of little or no relevance to developed countries, and for which international sources of default EFs, such as the EMEP/EEA Guidebook (EMEP/EEA, 2016), may not be appropriate. For sectors such as these, the workbook offers state-of-the-art default EFs sourced from the literature (a complete, fully referenced database of all default EFs is available for download: https://energycommunity.org/default.asp?action=IBC). The GAPF-EI tool also provides a basis for training and capacity enhancement in countries currently lacking emission inventory preparation expertise.

2.1. The GAPF-EI emission inventory preparation manual/workbook

The GAPF-EI manual (Vallack and Rypdal, 2019) provides methods for estimating anthropogenic air pollutant emissions from: fuel combustion and transformation; fugitive emissions from fuels; industrial processes (non-combustion); solvent and other product use; agriculture (including livestock enteric fermentation and manure management, application of fertilizers, methane from rice production, crop residue and savannah burning); other vegetation fires; and emissions from the treatment and disposal of wastes. In order to provide a standardized structure for use in compiling emission inventories, an Excel spreadsheet-based workbook (Vallack, 2019) accompanies the manual. Collectively, the manual and workbook are referred to as the 'GAPF-EI tool' and both are freely available on-line. The air pollutants covered are sulphur dioxide (SO_2), oxides of nitrogen (NO_X), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), methane (CH_4), ammonia (NH_3), particulate matter (speciated into PM_{10}, $PM_{2.5}$,

Table 1
The correspondence between emission source categories used in the GAPF-IE tool and those categories used in the 2016 EMEP/EEA Emission Inventory Guidebook and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. (The numbers are the source category codes used in each compendium.).

GAPF-EI Tool	EMEP/EEA (2016) Emission Inventory Guidebook	2006 IPCC Guidelines
1 Combustion in the Energy Industries	1.A.1 Energy industries	1 Energy (1A Fuel Combustion Activities)
2 Combustion in Manufacturing Industries and Construction	1.A.2 Manufacturing industries and construction	
3 Transport	1.A.3 Transport	
4 Combustion in Other Sectors	1.A.4 Small combustion	
5 Fugitive emission from fuels	1.B Fugitive emission from fuels	1 Energy (1B Fugitive Emissions from Fuels)
6 Industrial Processes	2 Industrial processes and product use	2 Industrial Processes and Product Use
7 Solvent and Other Product Use		
8 Agriculture	3 Agriculture	3 Agriculture, Forestry and Other Land Use
9 Vegetation Fires & Forestry	11B Forest fires	
10 Waste	5 Waste	4 Waste

black carbon (BC), organic carbon (OC)) and carbon dioxide (CO_2). Thus, the inventory methodology covers anthropogenic emissions of primary PM (as PM_{10}, $PM_{2.5}$, BC and OC), secondary inorganic aerosol precursors (SO_2, NO_X and NH_3), the O_3 precursors (NO_X, CO, NMVOC, CH_4) as well as two major GHGs (CO_2 and CH_4). Emissions of SO_2 comprise all sulphur compounds expressed in SO_2 mass equivalents; NO_X emissions include NO and NO_2 reported in NO_2 mass equivalents and all other emissions are reported as unit mass of the species concerned.

The emission source structure consists of ten sectors (Table 1) many of which are further sub-divided into subsectors (Table S1). The emission source categories are mainly based on the sectoral structure given in the EMEP/EEA (2016) Emission Inventory Guidebook approach used for preparing national emission inventories in Europe although they are also compatible with the Intergovernmental Panel for Climate Change (IPCC) 2006 Guidelines (IPCC, 2006). In particular, a clear distinction is made between energy and non-energy related emissions. The EMEP/EEA (2016) guidebook uses NFR (Nomenclature for Reporting) source category codes to identify each sector and subsector. The NFR codes are included for most subsectors in Table S1 and for the sub-subsectors included under sectors 6 and 7 below. Detailed descriptions of each subsector/sub-subsector by NFR code, can be found in EMEP/EEA (2016). For those subsectors not covered in the EMEP/EEA guidebook, detailed descriptions can be found in the IPCC (2006) guidelines.

The GAPF-EI workbook offers default emission factors (EFs) for each fuel and emission source sub-sector combination with footnotes detailing the reference source for each EF and any assumptions made in deriving them. However, the tool is flexible and allows the user either to choose the default EF offered or to enter an alternative EF if deemed more appropriate (e.g. one that is more specific to the local technology or conditions of use). Although for certain sectors, the main default EFs are Tier 1 factors from EMEP/EEA (2016) Guidebook and the IPCC (2006) Guidelines, for other sectors, especially those that are often of particular importance in LMICs, alternative default EF sources are suggested as described by sector below. After the activity data and EFs have been entered into the workbook by the user, emissions of each pollutant species are automatically calculated and displayed in a summary table.

2.2. Emissions from combustion in the energy industries (Sector 1) and in the manufacturing industries and construction (Sector 2)

For each pollutant species and sub-sector source category, the basic method used for calculating fuel combustion emissions is given in Equation (1).

$$E = A \times EF \times (100 - R)/100 \tag{1}$$

where, E = emission (kg), A = activity rate (TJ yr^{-1}), EF = emission factor (kg TJ^{-1}) and R = abatement/recovery efficiency (%).

Each emission factor (EF) is specific to the fuel used and assumed level of technology employed. The approach is similar to the EMEP/EEA (2016) and IPCC (2006) Tier 1 methods with the default EFs mainly coming from these two sources. The exception is for traditional charcoal production within the energy industries sector, for which the default EFs are from Bertschi et al. (2003) for earthen charcoal-making kilns in Zambia.

For SO_2, default EFs are not presented in the GAPF-EI tool because emissions depend on the sulphur (S) content of fuel, which varies considerably between fuel types and, for solid fuels, the degree of S retention-in-ash (USEPA, 1995). Thus, SO_2 EFs for fuel combustion are derived using the mass balance approach as shown in Equation (2):

$$EF_{SO2} = 2 \times S/100 \times 1/NCV \times (100 - SR)/100 \tag{2}$$

where, EF_{SO2} = Emission factor for SO_2 (kg MJ^{-1}), S = Sulphur content of fuel (%), NCV = Net calorific value of fuel (MJ kg^{-1}) and SR = Sulphur retention in ash (%). The two-fold multiplier at the beginning of Eq. (2) is required to convert from emissions as S (atomic wt. 32) to emissions as SO_2 (molecular wt. 64).

Default values, or ranges of values, for the S-content of fuels are given in the GAPF-EI workbook together with the relevant source references. For coal combustion, default S retention-in-ash values are derived from USEPA (1995): 5% for hard coal (i.e. coking coal, other bituminous coal and anthracite) in the power generation industry; 22.5% in transport and other sectors; and 25% for brown coal (i.e. sub-bituminous coal/lignite) in all sectors. For charcoal production, 100% of the sulphur in the feedstock wood is assumed to be retained in the charcoal given that wood with 0.015% S results in charcoal with 0.06% S (Smith et al., 2000) and 1 kg wood producing 0.28 kg charcoal (Bertschi et al., 2003). The S retention-in-ash value is assumed to be zero for liquid and gaseous fuels and negligible for solid biomass fuel combustion.

The emission abatement efficiency (R in eq. (1)) depends on the proportion of total capacity in a particular sector subject to controls. For SO_2, the default assumption is that emission controls for fuel combustion are insignificant except in cement manufacture and in the power generation sector. For coal used for cement manufacture, an S retention rate in the product of 80% is assumed (Kato, 1996). For the power generation sector, the proportion of coal- and oil-fired capacity subject to various types of SO_2 emission control is also taken into account. Emission controls for the power sector and industry are also provided for NO_X (for coal, oil and gas) and PM (for coal and oil). The efficiencies assumed for the various emission control devices for SO_2, NO_X and PM are from USEPA (1995) and emission controls for the other pollutants (CO, NMVOC and NH_3) are assumed to be insignificant.

For 'Combustion within manufacturing industry', provision is made for treating one subsector 'Brick Kilns' separately because traditional brick kilns are often a key source of air pollutants in LMICs. The default EFs offered in the GAPF-EI workbook for traditional brick kilns are from Weyant et al. (2014) for CO_2, CO, PM_{10}, $PM_{2.5}$, BC, and OC emissions from coal-fired brick kilns, and from Christian et al. (2010) for CO_2, CH_4, $PM_{2.5}$, BC and OC emissions from biomass-fired kilns. All remaining subsectors can generally be treated as one category 'Non-

Table 2
Default emission factors offered in the GAPF-EI tool for fuels commonly used in the residential sector.

Fuel	Pollutant species									
	CO_2 t/TJ	CO kg/TJ	CH_4 kg/TJ	NMVOC kg/TJ	NO_X (as NO_2) kg/TJ	NH_3 kg/t	PM_{10} kg/t	$PM_{2.5}$ kg/t	BC kg/t	OC kg/t
Charcoal	92.8[a]	4328[b]	222[d]	236[b]	70[b]	0.97[b]	2.38[c]	2.38[c]	1.19[d]	0.85[d]
Wood	101.7[a]	4260[e]	663[d]	1763[b]	73[e]	0.87[a]	8.3[e]	6.64[a]	0.83[a]	2.89[a]
Vegetal wastes	100.0[f]	5730[e]	300[f]	600[g]	47[e]	1.29[b]	8.05[e]	6.44[h]	1.0[i]	3.3[i]
Animal wastes	88.9[j]	3392[j]	383[j]	2057[j]	65.5[k]	4.75[a]	3.0[j]	3.0[j]	0.12[j]	1.8[j]
Coal	94.6[f]	2610[e]	300[f]	484[g]	34[e]	1.17[l]	14.8[m]	13.3[n]	2.2[m]	5.93[m]
Natural gas	56.1[f]	26[g]	5[f]	1.9[g]	5[g]	0.01[o]	0.061[g]	0.061[g]	0.0033[g]	0.027[p]
LPG	63.1[f]	26[g]	5[f]	1.9[g]	51[g]	0.01[q]	0.32[j]	0.31[n]	0.01[j]	0.06[j]
Kerosene	71.9[f]	57[g]	10[f]	0.69[g]	25[e]	0.005[l]	0.134[e]	0.081[g]	0.017[r]	0.013[s]

[a] Derived from Akagi et al. (2011).
[b] Derived from Bertschi et al. (2003).
[c] Smith et al. (2000).
[d] Assume 50% of PM is BC and 50% organic matter (assuming OC = OM/1.4) Bond et al. (2004).
[e] Zhang et al. (2000) for household stoves in China (For vegetal wastes, average EF for wheat and maize residues).
[f] IPCC (2006) Tier 1 default.
[g] EMEP/EEA (2016) Tier 1 EFs.
[h] Assumes $PM_{2.5}$ = 80% of PM_{10} as reported for wood and crop waste by Reddy and Venkataraman (2002a).
[i] Bond et al. (2004).
[j] Derived from Venkataraman et al. (2010) (for OC assumed = OM/1.4).
[k] Derived from Keene et al. (2006).
[l] Li et al. (2016) - value of 1.17 is for bituminous chunk coal in traditional stove (use 0.10 for advanced stove, for anthracite chunk use 0.20 (trad) and 0.08 (adv).
[m] Zhi et al. (2008).
[n] Assume a $PM_{2.5}/PM_{10}$ ratio of 0.9 for coal and 0.964 for kerosene and LPG (Reddy and Venkataraman, 2002b).
[o] Battye et al. (1994).
[p] Assume OC fraction is 8.33 x BC (Bond et al., 2004).
[q] Assume as for natural gas.
[r] Assume 13% of PM_{10} - Bond et al. (2004).
[s] Assume OC = BC/3.5 (Bond et al., 2004).

specified industry', the default EFs offered within GAPF-EI being mainly Tier 1 factors from EMEP/EEA (2016) and IPCC (2006).

2.3. Emissions from transport (Sector 3)

This sector includes emissions from the combustion of fuel during transport and, for road transport, unpaved road dust emissions. The categories included are road transport, civil aviation, railways, navigation and pipeline transportation. In the GAPF-EI tool, it is possible to choose from two alternative methods for road transport and aviation: a 'Simple method' and a 'Detailed method'. In the simple method, emissions of all pollutants are estimated in a way similar to that described above for fuel combustion in the power sector and industry, and this is also the method used for railways, navigation and pipeline transportation. The simple method is also recommended for estimating all SO_2 road transport and aviation emissions, which depend only on the S content of fuel, and for emissions of NMVOC, NH_3, CH_4 and CO_2 from road transport. For other pollutants from road transport, the simple method gives an approximate estimate of emissions and should only be used by countries lacking the data required for the preferred 'Detailed Method' or to obtain a first order estimate before more detailed work is undertaken. The default 'bulk EFs' (representing the whole road vehicle fleet) used for the simple method are mainly Tier 1 EFs from the IPCC (2006) for CO_2 and CH_4, and Tier 1 defaults for uncontrolled vehicles from EMEP/EEA (2016) for other pollutants. The exceptions are for particulate matter (PM_{10}, $PM_{2.5}$, BC and OC) where the defaults are derived from Bond et al. (2004) for 'gasoline, all vehicles, standards beginning' and for diesel assuming 80% 'on-road general, standards beginning' and 20% 'super-emitters'. In many developing countries, the so-called 'super-emitter' vehicles, especially poorly maintained diesel vehicles, can be responsible for large share of the transport fleet emissions (Bond et al., 2004; Klimont et al., 2017). Footnotes in the worksheets explain that the defaults can be customised to fit local circumstances.

In addition to fuel type, road transport emissions of NO_X, CO, NMVOC and PM (including BC and OC) also depend on the vehicle type (motorcycle, passenger car, light commercial vehicle, heavy duty vehicles etc.) and technology (e.g. Euro emission standards) and these variables are covered in the preferred 'Detailed method' offered in the GAPF-EI tool. The default exhaust EFs for the detailed on-road vehicle calculations are mainly derived from Tier 2 EMEP/EEA (2016) with Tier 1 maximum values from EMEP/EEA (2016) being suggested for uncontrolled vehicles commonly found in LMICs.

As many roads in LMICs are unpaved and represent a major source of dust (both PM_{10} and $PM_{2.5}$), a method for estimating these emissions is included in the GAPF-EI tool that requires as an additional input, the percentage dry days (< 0.25 mm precipitation) in a year. The method is based on that proposed by Gillies et al. (2005) for unpaved rural roads in dry weather. The PM_{10} EF = 3 x W x S g/km where S is the average speed in km/hr and W is the average vehicle weight in tonnes. Emissions of $PM_{2.5}$ are assumed to be 10% of PM_{10} emissions from unpaved public roads as suggested by the USEPA (2006).

For domestic aviation, the simple method is similar to the Tier 1 methods described in IPCC (2006) and EMEP/EEA (2016) based solely on total fuel consumption. A simple method, based on total fuel consumption alone, is not provided for international aviation because most of the emissions are from landing/take-off (LTO) cycles rather than from cruise emissions, which are largely international. The detailed methods for both domestic and international aviation require LTO data and are based on the EMEP/EEA (2016) Tier 1 method for jet kerosene (using EFs given on a representative aircraft basis).

2.4. Emissions from combustion in other sectors (Sector 4)

This sector includes emissions from fuel combustion in 'Residential' households, the 'Commercial/Institutional' sector, and in 'Agriculture, Forestry/Fishing'. For the residential sector, often a key source of air pollutants in LMICs, the default EFs for CO_2 and CH_4 are mainly from IPCC (2006). However, for other emitted species, many of the default EFs in the GAPF-EI tool are drawn from sources other than the EMEP/EEA Guidebook as this contains EFs derived for European countries that are often not appropriate for residential emission sources typical of developing countries, such as biomass cookstoves. Table 2 shows the GAPF-EI default EFs for fuels commonly used in the residential sector in LMICs together with source references and assumptions.

For the 'Commercial/Institutional' 'Agriculture, Forestry/Fishing' sectors, the default EFs are mostly derived from IPCC (2006) for CO_2 and CH_4, Battye et al. (1994) for NH_3 and EMEP/EEA (2016) for the remaining species.

2.5. Fugitive emissions from fuels (Sector 5)

This sub-sector covers all non-combustion activities related to the extraction, processing, storage, distribution and use of fossil fuels as well as combustion emissions from flaring. It includes fugitive emissions of NMVOC, CH_4 and CO_2 from crude oil exploration, production and transport, oil refining, the distribution and handling of gasoline (including emissions from service stations) and the production and distribution of natural gas (including venting). It also includes CH_4 emissions from underground and surface coal mining, during both mining and post-mining activities. In addition to NMVOC, CH_4 and CO_2, this subsector also includes fugitive emissions SO_2, NO_X and CO from oil refining, emissions of BC and OC from flaring during oil and gas extraction, and emissions of SO_2, NO_X, CO, NH_3, PM_{10}, $PM_{2.5}$, BC and OC from the production of coke. The methods are based on a combination of the Tier 1 IPCC (2006) and EMEP/EEA (2016) approaches with most of the default EFs coming from these two sources. However, fugitive NMVOC emissions from the handling and distribution of gasoline are estimated using the EMEP/EEA (2016) Tier 2 method that takes into account annual average Reid Vapour Pressure (RVP) and annual average ambient temperature. Accounting for the effect of ambient temperature on NMVOC emissions is particularly important for the LMICs located in the tropics. Also, the default EFs for BC (1.6 kg/10^3 m^3) and OC (1.6 kg/10^3 m^3) emissions during flaring are those typical of non-OECD countries provided by Klimont et al. (2017).

2.6. Industrial process (non-combustion) emissions (Sector 6)

Air pollutants can be emitted by a variety of industrial processes that chemically or physically transform materials, these non-combustion emissions being termed 'process emissions'. Emissions (E) are calculated using Eq. (1) except that in this case, A is the annual rate of production of the relevant commodity (as t yr^{-1}) and EF is the process EF (as kg t^{-1}). The industrial process emission sub-sectors and sub-sub-sectors covered by the manual are shown in Table 3. 'Fugitive emissions of PM from major construction activities' are included within this sector for convenience although strictly speaking, it is not a process emission. The majority of default EFs are either Tier 1 or Tier 2 factors from EMEP/EEA (2016) with additional defaults from IPCC (2006) and USEPA (1995).

2.7. Emissions from solvent and other product use (Sector 7)

Emissions are calculated by multiplying the activity rate (solvent use, t yr^{-1}) by an EF (kg NMVOC t^{-1}). The major sub-sectors and sub-sub-sectors covered in the manual are shown in Table 4. The default EFs are mainly Tier 2 EMEP/EEA (2016) uncontrolled factors and so may have to be adjusted to take account of control measures.

2.8. Emissions from agriculture (Sector 8)

Seven major types of agricultural activity are covered: livestock enteric fermentation, livestock manure management, animal housing, the application of nitrogenous fertilizers, rice cultivation, open-burning of crop residues, and savannah burning. Emissions are calculated by multiplying the activity rate (e.g. numbers of livestock, amount of fertilizer applied or annual crop production) by an EF. Enteric fermentation in ruminant livestock (e.g. cattle, buffalo, goats, sheep, camels), and to a lesser extent non-ruminant livestock (e.g. pigs, horses), can be a major source of CH_4 emissions in some countries. The IPCC

Table 3
The categories inventoried as industrial process emissions.

Sub-sector	Sub-sub-sector ([a]NFR code)
Mineral products	Cement production (2.A.1) Lime production (2.A.2) Asphalt roofing (2.D.3.c) Asphalt road paving (2.D.3.b)
Chemical industry	Ammonia (2.B.1) Nitric acid (2B.2) Adipic acid (2.B.3) Carbon black (2.B.10.a) Urea (2.B.10.a) Ammonium nitrate (2.B.10.a) Ammonium phosphate (2.B.10.a) Sulphuric acid (2.B.10.a) Titanium dioxide (2.B.6)
Metal production	Pig iron production (1.A.2.a) Aluminium production (2.C.3) Copper smelting (primary and secondary) (2.C.7) Lead smelting (primary and secondary) (2.C.5) Zinc smelting (primary and secondary) (2.C.6)
Pulp and Paper Industries	Kraft or Alkaline soda pulping (2.H.1) Acid sulphite pulping (2.H.1) Neutral sulphite semi-chemical (2.H.1)
Food and Drink	Alcoholic Beverages (2.H.2) Food Production (2.H.2)
Fugitive emissions of PM from major construction activities	

[a] NFR = Nomenclature for Reporting: source category codes used in EMEP/EEA (2016) Guidebook.

Table 4
The categories inventoried as emissions from solvent and other product use.

Sub-sector	Sub-sub-sector (NFR code)
Paint application (solvent based)	Industrial (2.D.3.d) Decorative (2.D.3.d) Unknown (2.D.3.d)
Paint application (water based)	(2.D.3.d)
Metal degreasing (open-top degreaser)	(2.D.3.e)
Dry cleaning of fabrics	(2.D.3.f)
Chemical products manufacture	Polyester processing (2.D.3.g) Polyvinylchloride (2.D.3.g) Polyurethane (2.D.3.g) Polystyrene foam (2.D.3.g) Rubber processing (2.D.3.g) Paints, inks and glues (2.D.3.g)
Other use of solvents	Mineral wool enduction (2.D.3.i, 2.G) Glass wool enduction (2.D.3.i, 2.G) Printing industry: Heat set offset (2.D.3.h) Publication gravure (2.D.3.h) Packaging (small flexography) (2.D.3.h) Fat, edible and non-edible oil (solvent extraction) (2.D.3.i, 2.G) Application of glue and adhesives (2.D.3.i, 2.G)

*NFR = Nomenclature for Reporting: source category codes used in EMEP/EEA (2016) Guidebook.

Tier 1 method for enteric fermentation is followed in the GAPF-EI tool with default EFs from IPCC (2006) included for nine animal categories. The method for livestock manure management covers emissions of NH_3, NO_X and CH_4 from the storage and disposal of livestock manures for 11 categories of livestock using Tier 1 default EFs for NH_3 and NO_X from EMEP/EEA (2016) and EFs for CH_4 from IPCC (2006).

Methods for estimating emissions of NH_3 and NO_X from eight different types of N-fertilizer are also covered. For NH_3, the EMEP/EEA (2016) Tier 2 EFs for warm countries (annual mean temperature > 25 °C) are offered by default whereas for NOx, the Tier 1 EFs from this source are used.

Disposal of agricultural crop residues by open-burning in the field emits SO_2, NO_X, CO, NMVOCs, CH_4, NH_3, PM_{10}, $PM_{2.5}$, BC and OC. In addition to annual production rates for the 11 crop types covered, the compiler must also estimate the fraction burnt in the field (rather than being used for fuel, animal fodder etc.). In general, Tier 1 default values from EMEP/EEA (2016) are provided for residue-to-crop ratio, dry matter fraction, and fraction oxidised. EMEP/EEA (2016) Tier 2 default EFs are included for most pollutants apart from CH_4 and OC, for which EFs are from Andreae and Merlet (2001), and SO_2 from Reddy and Venkataraman (2002a). Also, crop-specific default residue-to-crop ratios, appropriate for LMICs, were sourced from TIFAC (1991) and Tyagi (1989).

The method for estimating CH_4 emissions from rice cultivation provided in the GAPF-EI tool is based on the IPCC (2006) Tier 1 approach. The annual amount of CH_4 emitted from a given area of rice is a function of various factors including three rice ecosystem categories ('Irrigated continuously flooded', 'Irrigated intermittently aerated', and 'Rainfed and deep water') and so the total area under rice cultivation in the country will have to be apportioned between these three categories.

In GAPF-EI, savannah burning is included within the Agricultural sector as most of these fires are intentionally burned. The IPCC (1996) methodology is followed requiring an estimation of the amount of biomass burned (dry weight) based on the area of savannah burned during the inventory year, the fuel load biomass, and the fraction of this biomass that is actually burnt. Default values for fuel load and fraction burnt are from IPCC (1996), the default EF for $PM_{2.5}$ is from Andreae and Merlet (2001) and defaults for all other pollutants are from Sinha et al. (2003).

2.9. Emissions from vegetation fires and forestry (Sector 9)

This includes burning, other than savannah fires described above, that takes place during conversion of forests, woodlands, or grasslands to agricultural or other uses, prescribed burns for fire management or forest stand maintenance, and other vegetation fires started either accidentally by man or naturally by lightning. For each type of vegetation and for each pollutant species, emissions are calculated according to Equation (3).

$$E = A \times B \times EF \tag{3}$$

where, E = emission (t); A = annual area burnt (kha yr^{-1}); B = fuel biomass consumption (t ha^{-1}); and EF = emission factor (kg t^{-1} biomass burnt).

Default 'biomass consumption' values for the major vegetation types in GAPF-EI are from IPCC (2006) and the default EFs for individual pollutant species are from Andreae and Merlet (2001).

2.10. Emissions from the treatment and disposal of waste (Sector 10)

This sector covers the treatment and disposal of wastes including incineration/burning, disposal of wastes in landfills, and aerobic and/or anaerobic treatment of municipal sewage. In many developing countries, open-burning of Municipal Solid Waste (MSW), either next to residences, in the street or at waste dump sites, is a frequent disposal method (Wiedinmyer et al., 2014). For countries such as these, it can be assumed that all MSW, whether uncollected or taken to waste dumps, is effectively open-burnt. The annual amount of waste burnt is multiplied by the relevant EFs for each pollutant. For MSW, the default EFs are mainly from Akagi et al. (2011) for open burning and EMEP/EEA (2016) for incinerators (Tier 1 for modern and Tier 2 for uncontrolled plant). For industrial/commercial waste, EFs are mainly EMEP/EEA Tier 1 defaults for modern plant and USEPA (1995) defaults for uncontrolled plant.

Anaerobic decomposition of organic material within solid waste disposal sites (SWDS), commonly called 'landfill' sites, can be a major source of CH_4 emissions. For developing countries, it is often only the urban population whose waste is collected for disposal in SWDS. The method used in the GAPF-EI tool is essentially the IPCC (2006) Tier 1 methodology with default factors or ranges for factors taken from this source.

'Methane from domestic water' covers CH_4 emissions from the treatment and discharge of domestic wastewater (sewage). The IPCC (2006) Tier 1 method is used in which the calculation of emissions is separated by both income group (i.e. rural, urban high income, urban low income) and type of treatment system (latrine, septic tank, anaerobic reactor or deep lagoon, aerobic treatment plant, and untreated). A separate worksheet is provided for estimating NH_3 emissions from the storage of human excreta in latrines (simple dry toilets built outside the house) based on the EMEP/EEA (2016) methodology.

2.11. Default sources of activity data suggested in the GAPF-EI tool

If fuel use data for combustion sectors (Sectors 1 to 4) are not available from national sources, energy balance data, available for purchase from the IEA (IEA, 2018a), can be used instead. The IEA also provides by country (at no cost) consumption data for most fuels, in 5 year increments, in original units (kt) for coal, coal products, peat and oil shale/oil sands (IEA, 2018b) and for oil and oil products (IEA, 2018c), in terajoules (TJ) for natural gas (IEA, 2018d) and in GWh (1 GWh = 3.6 TJ) for renewables and waste (IEA, 2018e). For fugitive emissions from fuels (Sector 5), the default source of activity data for the production of crude oil, natural gas, gasoline and coke, and for gasoline consumption, is also the International Energy Agency database (IEA, 2019). For process emissions (Sector 6), default activity data sources include the online UN Industrial Commodity Statistics database (UN, 2019) for minerals products, certain chemicals and for food and drink production; the online FAOSTAT database for chemical fertilizer production and paper and pulp production (FAO, 2019); the Worldsteel Association (2019) for pig iron production and the United States Geological Survey (USGS, 2019) for all other metals. The default source of activity data for emissions from solvent and other product use (Sector 7) is the UN Industrial Commodity Statistics database (UN, 2019) and for Agriculture (Sector 8), and forest burning (Sector 9), the FAOSTAT database (FAO, 2019).

2.12. Case study application of the GAPF-EI tool to develop an emission inventory for Côte d'Ivoire

A national emission inventory for Côte d'Ivoire for the year 2010 was developed using the GAPF-EI tool following the methods detailed above. Not all sectors/subsectors were included in the inventory due to either the source not being present in Côte d'Ivoire (i.e. coal mining, coke production, production or metals, brick kilns, pipeline transport, production of chemicals, pulp and paper) or through a lack of activity data (civil aviation, solvent and other product use, production of food and alcoholic beverages, building construction activities). Default EFs, sources of activity data and methods, as described above for the GAPF-EI tool, were used for all source sectors apart from road transport and domestic kerosene lighting for which the default method was modified as described below. These were considered to be potential key source sectors for which activity data from international databases and the use of default EFs could be improved upon using more locally-applicable data.

For road transport, the detailed method was used with numbers of vehicles obtained from the International Organization of Motor Vehicle Manufacturers (OICA, 2019) for all vehicle types except motorcycles. Assamoi and Liousse (2010) used the fraction of households with motorcycles (11.8%) to estimate the total number of motorcycles in use in Côte d'Ivoire in 2002. In our study, this fraction was scaled up to 12.2% on the assumption that a change in possession and use of motorcycles was driven by the change in gross domestic product (GDP) between 2002 and 2010. Furthermore, due to the popularity of 2-stroke motorcycles, it was assumed that they accounted for the vast majority of the total motorcycle fleet with the remainder (assumed to be approximately 10%) consisting of 4-stroke motorcycles. We also assume the BC and OC emission factors (2.31 g kg^{-1} and 30.56 g kg^{-1} respectively) for 2-stroke motorcycles reported by Assamoi and Liousse (2010) for West Africa, also applied to Côte d'Ivoire in 2010. Where specific activity-related data for Côte d'Ivoire were unavailable, we assume data from neighbouring countries at a similar stage of development (i.e. Ghana or Nigeria) also applied. For example, for vehicle types other than motorcycles, in the absence of data for Côte d'Ivoire, the ratios of gasoline to diesel-fuelled vehicles and the average annual distances travelled by vehicle type were assumed to be the same as those reported for the neighbouring country of Ghana by the Ghana Environmental Protection Agency (Daniel Benefor, Personal communication). In many sub-Saharan African countries, vehicles are generally imported and second-hand (Keita et al., 2018), often with their catalytic converters subsequently removed (Roy, 2016). Also, the average age of vehicles in Africa is commonly more than 10 years (Mbandi et al., 2019; Kumar et al., 2008) and in Côte d'Ivoire it has been reported that most are over 20 years old (Keita et al., 2018). Therefore, in this study, we assume the EFs are equivalent to EMEP/EEA (2016) pre-Euro standards for all vehicle categories (except for BC and OC emissions from 2-stroke motorcycles referred to above).

In West Africa, a high percentage of roads are unpaved and therefore cause dust emissions when vehicles travel on them. In most cases, only an average of about a third or less of the entire road network in a country in Africa is paved while the rest is unpaved (Kumar et al., 2008; FMW, 2013; CIA, 2015). To calculate this source of emissions, distance travelled by vehicles on unpaved roads and the percentage of dry days in a year are also required. In the absence of national data, the distance travelled on unpaved roads in Côte d'Ivoire (expressed as percentage of total distance travelled) was assumed to be the same (16.2%) as that estimated for Nigeria (FMW, 2013), while the dry days in a year was estimated to be 40%.

In addition to its use for cooking, kerosene in West Africa is widely used for domestic lighting, either in simple wick lamps or in hurricane lamps. Emissions of products of incomplete combustion (PIC) from wick lamps can be substantial, with Lam et al. (2012) reporting emissions of BC from this source to be up 20 times higher than previous estimates. Therefore, we estimate emissions from domestic kerosene use in Côte d'Ivoire based on the estimate of Lam et al. (2012, supporting material) that in Western African, 24.5% of total kerosene use in the residential sector is for lighting of which 60% is used in simple wick lamps and 40% in hurricane lamps. Emission factors used for kerosene lighting were derived from those given in Lam et al. (2012) for typical field use of simple wick lamps (BC, 90 g kg^{-1}; OC, 0.4 g kg^{-1}; $PM_{2.5}$, 93 g kg^{-1} and CO, 11 g kg^{-1}) and hurricane lamps (BC, 9 g kg^{-1}; OC, 0.5 g kg^{-1}; $PM_{2.5}$, 13 g kg^{-1}; and CO, 3 g kg^{-1}). For all other species, the default GAPF-EI EFs as described above in Section 2.4 were used for domestic kerosene use.

2.13. Uncertainty analysis

An uncertainty analysis of the emissions inventory for Côte d'Ivoire was carried out based on the IPCC (2006) error propagation methodology, in which uncertainty is expressed as a 95% confidence interval (i.e. there is a 95% probability that the actual value is within the interval defined by the confidence limit). The default sources of EFs used in the analysis (EMEP/EEA, 2016; IPCC, 2006) include the lower and upper limits of the 95% confidence interval, defined by the 2.5 percentile and 97.5 percentile of the cumulative distribution function of the estimated EF. As described above, certain EFs used in the inventory were from sources other than EMEP/EEA or IPCC, and for some of these, uncertainties are expressed as ± the standard deviation (SD) of the mean value. For these EFs, the upper and lower 95% confidence intervals were taken to be ± twice the SD (expressed as percent of the emission factor). Uncertainties around the activity data were also taken into account in this analysis, the higher end of the uncertainty ranges given in EMEP/EEA (2016) for non-OECD countries being assumed to apply, that is ± 10% for both IEA energy statistics and UN databases. For other sources of activity data, the IPCC (2006) indicate an uncertainty range of 30–100%. We applied the top end of this range, interpreted as a 2-fold uncertainty (i.e. +100%–50%), to the quantity of municipal solid waste (MSW) generated (activity data for CH_4 from landfill), the amount of MSW open-burnt, and for road transport, the vehicle kilometres travelled (VKT) by each type of vehicle.

All uncertainty bounds around the central values were first converted into percentages (+x%, -y%) before being combined, the upper and lower bounds being calculated separately. Where the uncertain quantities were to be combined by multiplication (e.g. EF x activity rate), the combined uncertainty was calculated as the square root of the sum of the squares of the individual % uncertainties. This is the 'root-sum-squares' method - also termed the 'Rule B' method in Chapter 3 of the IPCC (2006) Guidelines. Also, the IPCC (2006) 'Rule A' method was applied where the uncertain quantities were combined by addition, such as emissions of a particular pollutant species from each of several different fuels used within the same sector. In the 'Rule A' method, the individual % uncertainties are first weighted according to each fuel's contribution to the total emission of the species for that sector, with the 'root-sum-squares' of the weighted percentages then producing the combined uncertainty. As an emission inventory is essentially the sum of products of EFs and activity data, Rules A and B were used repeatedly to estimate the combined uncertainty in total emissions for each pollutant species. Lastly, the combined percent uncertainties calculated for the upper and lower bounds around the totals were converted into absolute quantities for inclusion in the results tables below.

3. Results and discussion

3.1. Emission inventory for Côte d'Ivoire for 2010

The 2010 emission inventory totals for Côte d'Ivoire for each species, together with uncertainty estimates, are shown in Table 5. (A detailed breakdown of emission estimates by sector/subsector is given in Table S1). As expected for an inventory dominated by combustion sources, emissions of CO_2 and CO were much greater than emission of the other species. Emissions of PM_{10} are also very high due to the inclusion of unpaved road dust which accounted for 306 Gg out of the 565 Gg total. Of the remaining species, emissions of NMVOC and CH_4 were the next highest followed by $PM_{2.5}$ (predominantly OC), NO_X, NH_3 and lastly SO_2. Uncertainty around the total estimates was lowest for CO_2 (± 5%) and highest for NMVOC (−36%, +29%) with, for the remaining species, the lower bounds ranging from −15% to −25% and upper bounds ranging from +16% to +28%. The differences in combined uncertainty in total emissions between species largely reflects the uncertainties associated with the EFs given that uncertainty in activity data was assumed to be ± 10% in nearly all cases as described in Section 2.12. For example, the largest sources of NMVOC emissions were wood fuel combustion in the residential sector (200 Gg yr^{-1}; EF uncertainty ± 78%) and charcoal manufacture (122 Gg yr^{-1}; EF uncertainty −67% + 200%). Conversely, for CO_2, uncertainty for the EFs

Table 5
Summary of total national emissions in 2010 for Côte d'Ivoire with combined uncertainty expressed as the lower and upper bounds of the 95% confidence interval (uncertainty also expressed, in parentheses, as ± percentage difference from total).

	SO_2 Gg yr^{-1}	NO_X Gg yr^{-1}	CO Tg yr^{-1}	NMVOC Gg yr^{-1}	NH_3 Gg yr^{-1}	PM_{10} Gg yr^{-1}	$PM_{2.5}$ Gg yr^{-1}	BC Gg yr^{-1}	OC Gg yr^{-1}	CH_4 Gg yr^{-1}	CO_2[a] Tg yr^{-1}
Total	33.0	187	2.82	511	91.5	566	232	20.2	99.6	414	12.8
Lower bound	27.6	151	2.25	325	68.5	483	189	15.7	77.5	321	12.1
	(-16%)	(-19%)	(-20%)	(-36%)	(-25%)	(-15%)	(-19%)	(-22%)	(-22%)	(-22%)	(-5%)
Upper bound	41.2	235	3.38	661	113.7	662	276	26.4	128	478	13.5
	(+25%)	(+26%)	(+20%)	(+29%)	(+24%)	(+17%)	(+19%)	(+31%)	(+28%)	(+16%)	(+5%)

[a] Excludes biogenic CO_2 emissions from crop residue burning, savannah and other vegetation fires.

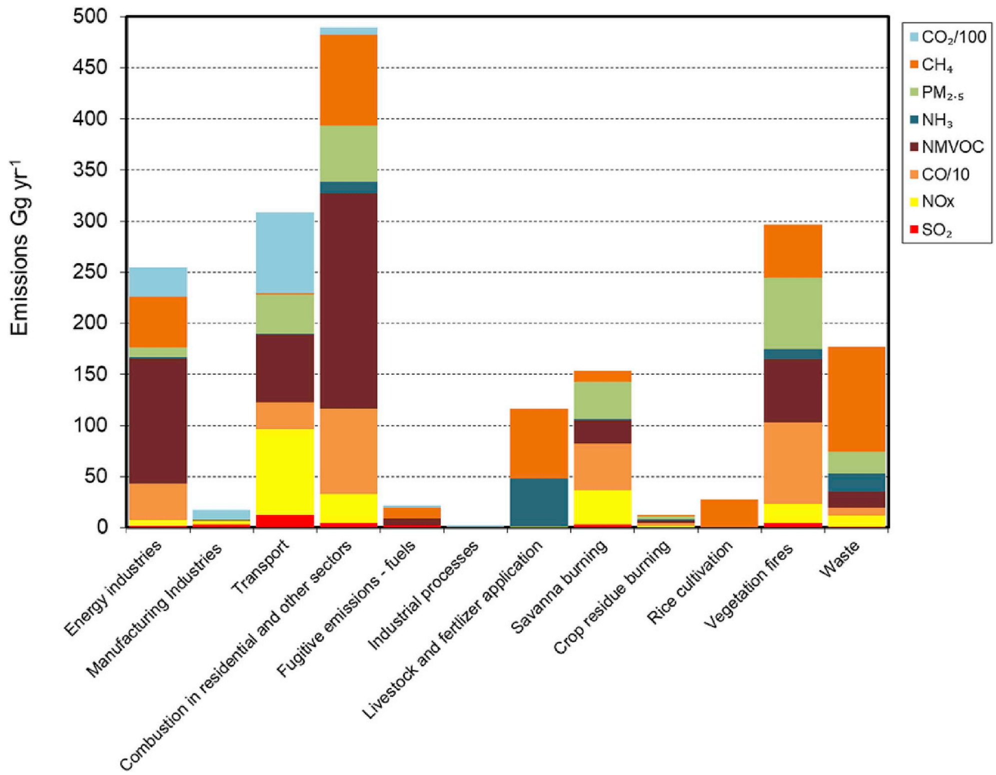

Fig. 1. Contribution of pollutant species to total emissions for Côte d'Ivoire by source sector in 2010. (NB: Emissions of CO are divided by 10 and emission of CO_2 divided by 100).

was generally only ± 2% to ± 4%.

Fig. 1 shows that the most important sector for the air pollutant (i.e. excluding CO_2) emisions was 'Combustion in residential and other sectors' followed by 'Vegetation fires', 'Transport', 'Energy industries', 'Waste', 'Savanna burning and other agricultural activities' (Livestock and fertlizer application, Crop residue burning and Rice cultivation). For (non-biogenic) CO_2, the transport sector (mainly road transport) and the energy industries (mainly natural gas combustion in electricity generation) were the most important emission sources. The major sources of CO were 'Combustion in residential and other sectors' (predominantly domestic solid biomass combustion), 'Vegetation fires' (mainly forests), 'Savannah burning' and the 'Energy industries' (mainly charcoal manufacture).

Fig. 1 and Table S1 show the particular importance of NMVOC emissions in the Côte d'Ivoire inventory, the most important source sectors (Fig. 2) being 'Residential' (mainly solid biomass combustion, 'Energy Industry' (mainly charcoal making within the Manufacturing of Solid Fuels sub-sector)', 'Transport' (mainly road transport) and 'Vegetation fires' (mainly forest). Methane (CH_4) emissions are also significant for several sectors especially 'Waste' (mainly domestic wastewater), 'Residential' (solid biomass combustion, 'Livestock' (mainly enteric fermentation in livestock and rice cultivation, 'Vegetation fires' and 'Energy Industry' (mainly charcoal making). The transport sector was the largest source of NO_X emissions (mainly diesel combustion in road transport) followed by emissions from savannah burning and solid biomass combustion in the Residential sector. For $PM_{2.5}$ emissions, the most important sources were forest fires, domestic solid biomass combustion, savannah burning and, within the transport sector, dust from unpaved roads. The most significant source of NH_4 emissions was livestock manure management.

Fig. 3 summarises the results of a more detailed analysis for fine particulate matter ($PM_{2.5}$) speciated into black carbon (BC), organic carbon (OC) and 'Other $PM_{2.5}$' (i.e. non-carbonaceous $PM_{2.5}$ such as ash, salts and crustal material). The mass of 'Other $PM_{2.5}$' was calculated as total $PM_{2.5}$ minus the sum of BC plus Organic Carbon Mass (OCM), where OCM was calculated as the OC multiplied by 1.4 to account for the non-carbon additional mass attached to OC aerosols (Park and Jacob, 2003). This figure and Table S1 show that the residential sector in Côte d'Ivoire was the largest source of BC emissions (8.0 Gg), mainly from wood and charcoal fuelled cookstoves (7.1 Gg), but with a significant contribution (0.9 Gg) from kerosene use (mainly in simple wick lamps). The residential sector was also a significant source of OC although open burning of vegetation (forest fires and savannah burning) accounted for most of the OC emissions. Within the waste

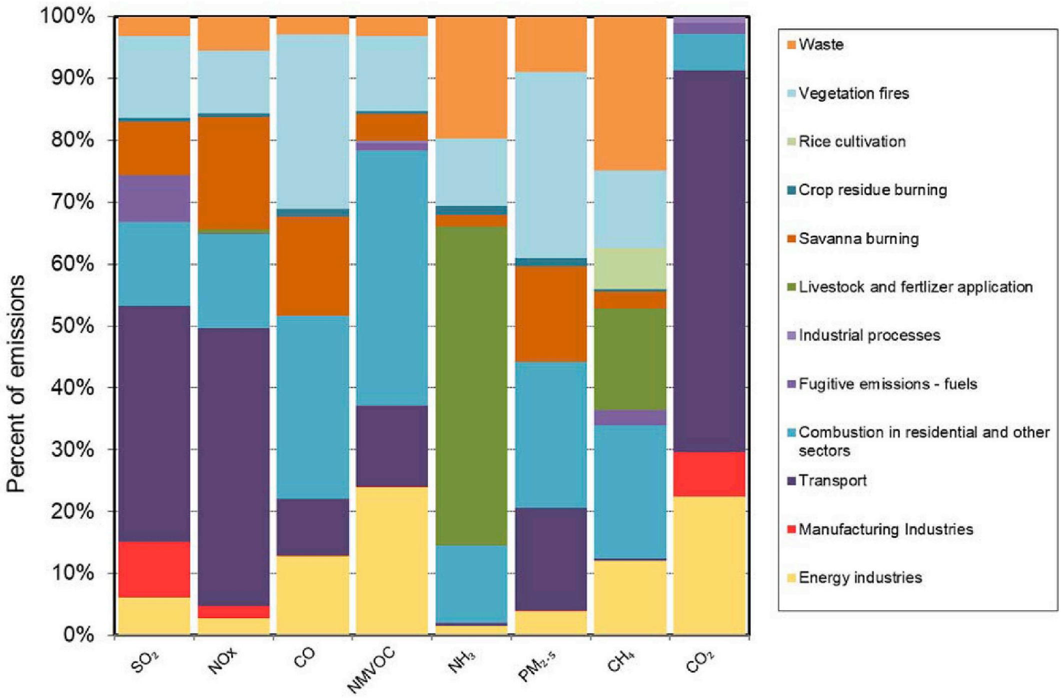

Fig. 2. Percentage sectoral breakdown of Côte d'Ivoire 2010 emissions by species. (Note: 'Energy industries' includes traditional charcoal production; and 'Transport' includes $PM_{2.5}$ emissions from unpaved road dust.)

sector, open burning of municipal solid waste (MSW) also contributed to the $PM_{2.5}$ emissions, particularly in the form of OC (11.2 Gg). The largest source of 'Other $PM_{2.5}$' emissions was the transport sector, predominantly unpaved road dust (30.6 Gg), although residential biomass fuel combustion (15.5 Gg) and open burning of forests (12.9 Gg) and savannah (13.5 Gg) were also significant sources. Fugitive dust emissions from unpaved roads are part of what is termed 'anthropogenic fugitive, combustion, and industrial dust' (AFCID) emissions of which are often excluded from inventories and so their contribution to $PM_{2.5}$ mass remains poorly quantified and is partially missing or strongly under-represented in global models (Philip et al., 2017). Although coarse particles that settle close to the road account for the most of the unpaved road dust emissions, there is still a portion that contributes to $PM_{2.5}$. In this study, on the assumption that $PM_{2.5}$ comprises 10% of PM_{10} emissions from unpaved roads (USEPA, 2006), this constitutes a significant source of fine PM in Côte d'Ivoire. These results

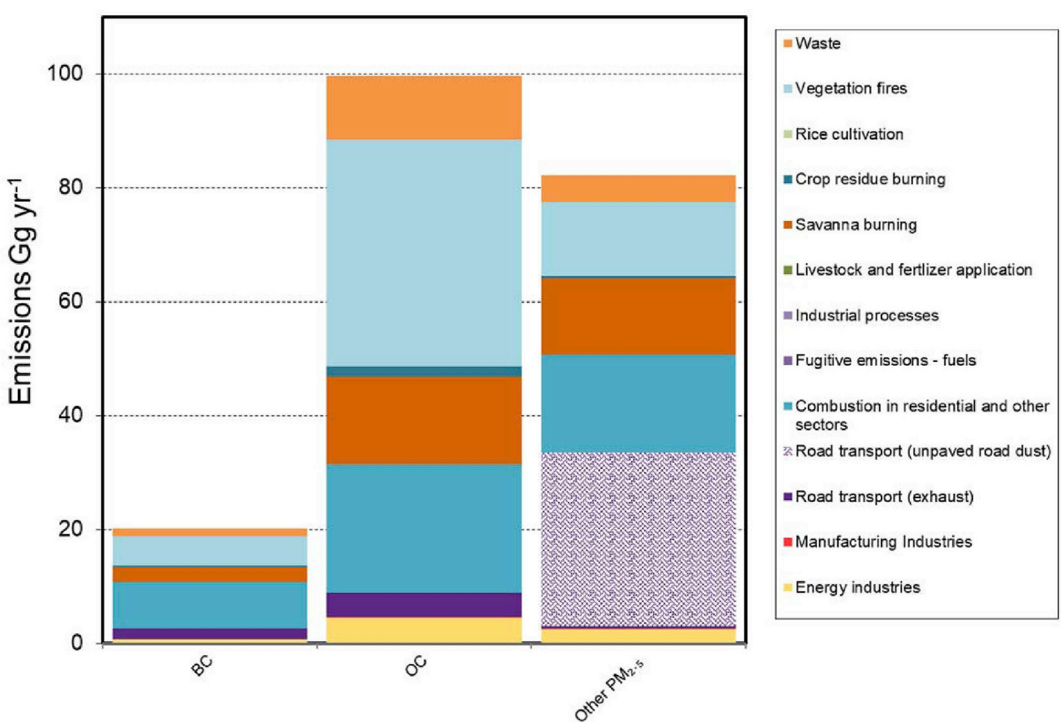

Fig. 3. Sectoral breakdown of Côte d'Ivoire emissions of fine particulate matter speciated into black carbon (BC), organic carbon (OC) and other $PM_{2.5}$. (Other $PM_{2.5}$ = Total $PM_{2.5}$ - (BC + OC*1.4)).

emphasise the importance of including traditional technologies and practices (residential use of biomass cookstoves and kerosene wick lamps, open burning of MSW), driving on unpaved roads and open vegetation burning (forests and savannah) in order to gain a full understanding of $PM_{2.5}$ emissions from developing countries such as Côte d'Ivoire.

3.2. Comparisons with other emission estimates for Côte d'Ivoire

Two main sources of emission estimates are available for comparison with this study, both having global coverage that include results for Côte d'Ivoire in 2010. The first is from the Emissions Database for Global Atmospheric Research (EDGAR) v4.3.2 (EDGAR, 2019), described by Crippa et al. (2018), and the second is the GAINS model (Greenhouse gas - Air pollution Interactions and Synergies) Eclipse v5a dataset (GAINS, 2019) developed by the International Institute for Applied Systems Analysis (IIASA) and described by Stohl et al. (2015). In order to enable direct comparisons with the two global initiatives, results from this study are presented both with and without emissions from vegetation burning (savannah and forest fires) and dust from roads, given that emissions from these sectors were not included in the EDGAR and GAINS Eclipse datasets. Therefore, all the comparisons below are for the second, adjusted set of results from this study.

Table 6 shows that for all pollutants apart from NO_X, the adjusted results from this study lie somewhere between those for EDGAR and GAINS Eclipse. For CO, NH_3, $PM_{2.5}$, BC, OC, results from this study are closer to those for EDGAR whereas for NO_X, NMVOC, PM_{10} and CH_4 they are closer to the GAINs Eclipse results. The relatively high values reported here for NO_X are largely due to emissions from transport (mainly on-road vehicles) which were 84.0 Gg yr^{-1} in this study compared with 22.4 Gg yr^{-1} in GAINS Eclipse and 17.5 Gg yr^{-1} reported in EDGAR. The likely reason for the large difference is the source of road transport activity data used and the level of detail of the analysis. The GAINS Eclipse and EDGAR estimates both rely on fuel consumption data reported by IEA (2019) whereas in this study, an alternative approach was adopted using nationally-specific vehicle numbers and annual average distances travelled by vehicle type (as described in Section 2.11) and applying vehicle-specific EFs (in g/km) from EMEP/EEA (2016).

It is interesting to note the very large differences in NMVOC emissions between all three inventories. The adjusted total for this study (426 Gg yr^{-1}) is somewhat higher than that for GAINS Eclipse (296 Gg yr^{-1}) but considerably lower than the EDGAR estimate (1307 Gg yr^{-1}). The reason that the result in this study is higher than those for GAINS Eclipse may be due to the particularly high emissions of NMVOC (122 Gg yr^{-1}) from traditional charcoal manufacture in this study compared with only 1.2 Gg yr^{-1} for the whole of the energy sector in GAINS Eclipse. In the EDGAR database, the high NMVOC emission estimate appears to be largely due to the 1106 Gg yr^{-1} from 'Fugitive emissions from solid fuels', a category that normally applies to coal mining and handling activities. Given the lack of coal mining in Côte d'Ivoire, it may be that in EDGAR, charcoal manufacture is included under this category, although this would only partly explain the big difference with our estimate. Reasons for the large differences in NMVOC estimates between the three inventories warrant further investigation.

Table 6
Côte d'Ivoire emissions for 2010 from this study compared with estimates from global initiatives.

Species	Units	This study	This study adjusted (i.e. without emissions from savannah and other vegetation fires and road dust)	EDGAR (v4.3.2)	GAINS Eclipse v5a
SO_2	Gg yr^{-1}	33.0	25.8	18.0	33.3
NO_X	Gg yr^{-1}	187	133	45.7	58.1
CO	Tg yr^{-1}	2.82	1.57	1.48	1.83
NMVOC	Gg yr^{-1}	511	426	1307	296
NH_3	Gg yr^{-1}	91.5	79.8	79.7	68.8
PM_{10}	Gg yr^{-1}	565	155	262	185
$PM_{2.5}$	Gg yr^{-1}	232	95.8	87.9[a]	168
BC	Gg yr^{-1}	20.2	12.6	12.1	28.6
OC	Gg yr^{-1}	99.6	44.5	33.5	68.9
CH_4	Gg yr^{-1}	414	351	398	319
CO_2	Tg yr^{-1}	12.8	12.8	6.78	

[a] Combined $PM_{2.5}$ estimate for fossil fuel and biomass (including crop residue) burning.

Other comprehensive air pollutant emission inventory or source apportionment studies for Côte d'Ivoire, with which comparisons of our results could be made, are lacking. However, our results are generally in agreement with regional studies of atmospheric composition in West Africa indicating that combustion related aerosols are mainly emitted from biomass burning (mainly savanna fires), domestic fires (fuelwood and charcoal) and fossil fuel sources (traffic, industry) (Liousse et al., 2010).

3.3. Applicability of the GAPF-EI tool to Côte d'Ivoire

The GAPF-EI tool is an emission inventory preparation aid that has been applied here to compile a 2010 emission inventory for Côte d'Ivoire covering all the major air pollutants and precursors as well as two major GHGs (CO_2 and CH_4). Its transparency and user-friendly design makes it an ideal tool for capacity building and in-country practitioner use. Its inherent flexibility, in terms of allowing the user to employ locally-relevant EFs (if available) instead of the defaults, and freedom to use national activity data if preferred, makes it an ideal tool for LMICs. In particular, it is designed to enable users to estimate emissions from sources that may be of particular relevance to developing countries. Hence for Côte d'Ivoire, emissions could be estimated for sectors such as traditional biomass cookstoves, kerosene wick lamps, traditional charcoal manufacture, transport on unpaved roads, open-burning of MSW and crop residues, and savannah burning – sectors that are not always well-characterised in national inventories. The GAPF-EI approach also covers emissions of all species that contribute to adverse impacts on air quality, which is often a bigger concern than climate change in many LMICs due to its large and growing impacts, especially on human health. Thus, the approach includes both the secondary inorganic aerosol precursors (NO_X, SO_2 and NH_3) and the ozone precursors (CO, NO_X, NMVOC and CH_4) in addition to primary PM (including BC and OC) and CO_2. This means that if required, the results of the inventory could be used as inputs to atmospheric chemistry transport models to derive the resultant impacts on ambient $PM_{2.5}$ and O_3 concentrations in addition to net impacts on radiative forcing of all relevant species (both warming and cooling). Thus, the GAPF-EI approach can be used to go on to explore the air pollution and climate change co-benefits of mitigation measures. To this end, the GAPF-EI methodology has recently been incorporated within an application of the Low Emissions Analysis Platform (LEAP) scenario analysis tool described by Heaps (2020).

The GAPF-EI tool's use of default EMEP/EEA (2016) EFs developed for high-income countries, might be expected to introduce an extra degree of uncertainty for a LMIC such as Côte d'Ivoire, possibly biasing some estimates. However, the reliance on Tier 1 EMEP/EEA defaults (that assume a European average level of technology) was mainly confined to combustion in the manufacturing industry, industrial process emissions and solvent and other product use, all of which were relatively minor components of the Côte d'Ivoire inventory (Fig. 1). Transport was a major contributor, but for this sector we mainly used the EMEP/EEA (2016) default EFs for pre-Euro standard vehicles, which we considered appropriate for Côte d'Ivoire. The energy industries were also a major source sector but, as Table S1 shows, this was dominated by emissions from traditional charcoal production for which

Africa-specific EFs were used from the literature. For all the other major contributing sub-sectors (Table S1), EMEP/EEA (2016) Tier 1 EFs were not used. It will often be the case in LMICs (as in Cote d'Ivoire) that the most important contributing sectors will be those for which the GAPF-EI approach either offers default EFs from the literature that are more relevant for LMICs, or selects EMEP/EEA guidebook EFs that are appropriate for LMICs. We conclude that the GAPF-EI approach is an appropriate tool for both capacity building and EI development within LMICs.

4. Conclusions

Application of the GAPF-EI tool to Côte d'Ivoire has demonstrated its suitability for use in a LMIC context where traditional technologies and practices are often found to be important contributors to air pollutant and GHG emissions. In Côte d'Ivoire, these included the residential use of traditional biomass cookstoves and kerosene wick lamps, traditional charcoal manufacture, driving on unpaved roads, and open burning of MSW. The option to include emissions from savannah burning and other vegetation fires, often important emission sources in Africa and LMICs elsewhere, enables users to gain a more complete picture of the emission impacting their air quality. The emission estimates for Côte d'Ivoire largely fall within the range of values reported by two major global initiatives giving credibility to the results. It is important to note that outputs from the GAPF-EI tool can also support the development of mitigation scenarios for low emission development plans to address SLCPs, air pollutants and GHGs and particularly, the development of integrated air quality and climate change strategies.

CRediT authorship contribution statement

Harry W. Vallack: Writing - original draft, Conceptualization, Methodology, Software. **Olajide O. Olawoyin:** Investigation, Formal analysis, Writing - review & editing. **W. Kevin Hicks:** Writing - review & editing. **Johan C.I. Kuylenstierna:** Conceptualization, Funding acquisition, Writing - review & editing. **Lisa D. Emberson:** Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2020.05.023.

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